8. Light

(typos fixed 30 Oct 2005)

High Tech Light

Light is full of surprises. Even in the mid to late 20^{th} century, many of the following applications were not anticipated.

Fiber optics. We once thought we would send all our information by satellite, relaying microwave signals to carry millions of telephone conversations at the same time. But we found a better way: send the signals with light, using "fiber optics" buried under the sea floor.

> Why is light so much better than microwaves? How do fiber optics work? Why are they sometimes called "light pipes"?

Multispectra. With our eyes, we see what appears to be an infinity of different colors. But multispectral cameras can see many more. They see colors that can indicate the health of the vineyard, or the status of moisture in the soil of China.

> What is it they see that we don't?
> (Hint: they see the same light we see. They just turn it into a larger number of colors. But what does that mean? Don't we already see an infinite number of colors?)

Spy satellites photograph suspect nuclear facilities in other nations. The satellites must fly low, in order to get good photos. But that means they are over the object of interest for less than a minute (since they are moving 5 miles per second).

> Why can't they fly high, get a view that lasts, and just use a powerful telescope? What feature of light makes low earth orbit the preferable one?
> (Hint: it is related to the fact that light is a wave.)

Laser induced nuclear fusion. The most powerful way of delivering energy to a small spot is with light. Laser beams directed at small pellets of tritium and deuterium can cause the isotopes to combine, a process called nuclear fusion, releasing energy.

> What properties of *light* makes it the best way to heat pellets to the extremely high temperatures required?

Computer screens. If you look at a white TV computer (or TV) screen up close, with a magnifying glass, you won't see any white at all. You'll see red, green, and blue spots. Try it.

> Why does it look white from a distance? What is color, really? Where does the color sparkles of diamonds come from? Or the color of rainbows (which comes from water droplets)? Why do music CDs look like rainbows when put in sunlight?

What is light?

As the above examples were meant to show, light is a puzzling phenomena, with properties that seem to make no sense.[1] Yet, if you understand them, they have important uses and applications that you otherwise would never guess.

The key to understanding the behavior and properties of light is to recognize that light is actually a wave. But light doesn't *seem* to be a wave. And if light is a wave, what is waving? For water waves, the water is waving. For earthquakes, the Earth is quaking. For sound, the air is shaking. But what is moving when a light wave waves?

Here's the answer, and don't worry if it sounds abstract: light is a wave consisting of a vibrating electric and magnetic field. Light is an "electromagnetic wave." Previously in this book I've mentioned that the "vacuum" can vibrate. The electric and magnetic fields are part of this vacuum. They are the aspects of the vacuum that wave when light is present.

If you shake the air, a wave of sound is emitted. If you shake the ground (by the sudden release of a fault), an earthquake is emitted. If you shake some water, a water wave is emitted. If you shake an electron, an electromagnetic wave is emitted. A vibrating electric and magnetic field move together away from the electron, carrying energy. When this electromagnetic field hits an electron it puts a force on it, in the same way that sound exerts a force on your eardrum, or an earthquake exerts a force on a building.

If light is a wave, why doesn't it look and feel like a wave? The answer: because its frequency is extremely high, and its wavelength is very short.

The average wavelength for visible light is about 0.5 microns = 0.5×10^{-6} meters. Recall that the diameter of a human hair is 25 to 100 microns. So the crests of light waves are so close, that you can't easily detect the individual crests. From this wavelength, we can calculate the frequency of light using the equation for waves that

$$v = f\,L$$

We now set v = speed of light = 3×10^{8} meters per second, equivalent to one foot per typical computer cycle.[2] Then $f = v/L = (3 \times 10^{8})/(0.5 \times 10^{-6}) = 6 \times 10^{14}$ cycles per second =

[1] Even Newton, the inventor of physics (died in 1727), came up with a wrong theory for light, even though he got almost everything else in physics right.

[2] Recall that this also works out to be equal to 30 cm per nanosecond (10^{-9} sec). Since 30 cm is about 1 foot, and a nanosecond is about one computer cycle (for a 1 GHz computer), this means that the speed of light is about 1 foot per computer cycle. If you have a faster computer, e.g. 2 GHz, then light travels only 15 cm, i.e. 6 inches in one cycle.

6 x10^{14} Hertz. That's very fast. Every nanosecond (i.e. every computer cycle) such light vibrates nearly a million times. No wonder we don't notice that it is a wave.

The high frequency of light is the key feature that has made light the main system for carrying information. Most of the internet, and most of our telephone system, sends its signals in the form of light, guided by fiber optic "light pipes". To understand why, we delve a little into the theory of information.

Laser communications – and information theory

Computers keep all their information stored in terms of the numbers 0 and 1. Each stored number is called a "bit" of information. If you want to send the letter A, then you combine eight of these bits into a code that represents the letter "A". The most widely used code is called ASCII.[3] In this code, the binary bits for the letter A are 00001010. The letter B is 00001011. Note that only one bit is different. C is 00001100. (No, you don't have to learn these.) Everything the computer does is translated into strings of 0 and 1 for computation purposes. (Yes, you should know that.)

Modern communication works the same way. If you want to send a telephone conversation across the United States, the electronics will first encode it into a long string of 0 and 1s, and then send these. The more such signals you can send per second, the more information you can send. To send a signal using light, one way is to turn it on and off, with on representing 1, and off representing 0. The number of bits that you can send every second is called the "baud rate" *R*.

The "theory of information" was invented by Claude Shannon in the middle 1940s, and he discovered the most important results. Perhaps the most significant of these is that you can not really send signals faster than the frequency of the wave that you are using. This important equation can be written[4]:

$$R = f$$

In Shannon's simple equation, *f* is the frequency of the signal (either light, radio waves, or microwaves), and *R* is in bits per second (*baud*). This equation says that the bits per second that can be sent is approximately equal to the frequency of the wave being used.

That's what makes fiber optics so valuable. Fiber optics use light to send signals, and the frequency of light is very high, approximately 6 x10^{14} cycles per second, i.e. 600,000

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[3] ASCII stands for American Standard Code for Information Interchange.

[4] This footnote is for those who are interested in some of the details. What Shannon really proved was that the information rate was given by R = B $\log_2$(S/N). In this equation, B = f_H - f_L is called the "bandwidth". (f_H is the highest frequency you can use, and f_L is the lowest. $\log_2$ means logarithm to base 2.) This means that B is less than the higher frequency f_H. S/N is the signal-to-noise level. The $\log_2$ factor is a bit greater than 1, so that makes R a little bigger. If $f_H \gg f_L$, then R $\approx f_H$.

GHz. That means that fiber optics can send this many bits per second. In contrast, telephone lines, which have a maximum frequency of a few megahertz, can only send a few million bits per second. Fiber optics is almost a billion times better.

Shannon's equation, $R = f$, has a simple interpretation. You can't make a wave vary faster than its own frequency f. You can turn it on and off, but not faster than f times per second. [5] So the maximum number of bits you can send every second is the frequency of the light.

Remember this: *the frequency tells you the number of bits per second you can send.*

Color

Even though light vibrates very fast, our eyes can still distinguish light of different frequencies. The common word for light frequency is *color*. Red light has a wavelength of about 0.65 microns = 650 nanometers, and that works out to a frequency of 4.6 x10^{14} Hz. Blue light has a wavelength of about 0.45 microns = 450 nm, and that means its frequency is about 7 x10^{14} Hz. These numbers are illustrated in the diagram below.

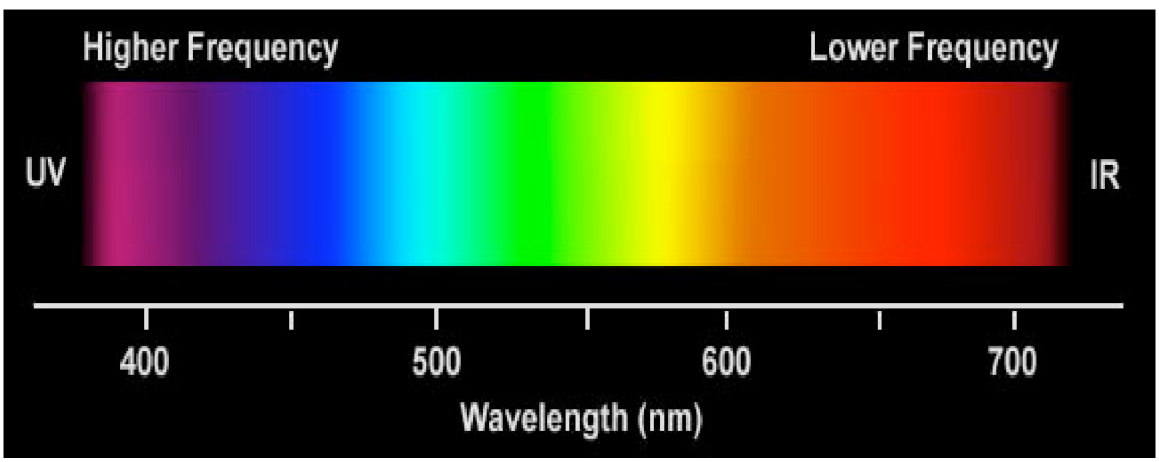


Figure: Color and frequency. Wavelength is shown in nanometers (nm). One nanometer is 10^{-9} meters = 10^{-3} microns. So 500 nanometers (light blue in the figure) is 0.5 microns.

The colors shown in the figure resemble the colors of the rainbow, and that's because they are. "White light" consists of a mixture of all these colors. When they all arrive into our eye, our brain calls the color "white." White light does not consist of a single frequency, but of a mixture of light of different frequencies. Some people would put it

[5] In Shannon's theorem, the B is actually the "channel capacity," i.e. the maximum rate that you can vary the signal. If you make a signal vary faster than f, you are actually making the frequency higher.

this way: "white is not a pure color." That statement is true if, by "pure", you mean it contains only a single frequency of vibration.

The rainbow is created when sunlight passes through raindrops. Light with different frequencies bends, when passing through the raindrop, into different directions. This process of bending is called refraction, and we'll discuss it further in a moment. But the bending makes the different colors in the white light go out in separate directions, and that's what makes the rainbow.

Note in the figure that beyond red, at long wavelengths, is a region marked ***IR***. That stands for ***infrared***. It is light, but just not visible to the human eye. Off to the left (very short wavelengths) is ***UV***, which stands for ***ultraviolet***. That is also invisible to our eyes. We'll talk more about these invisible colors in the next chapter. UV is, in fact, the color that is most responsible for the ozone layer in the atmosphere. It is the color that produces the worst sunburns.

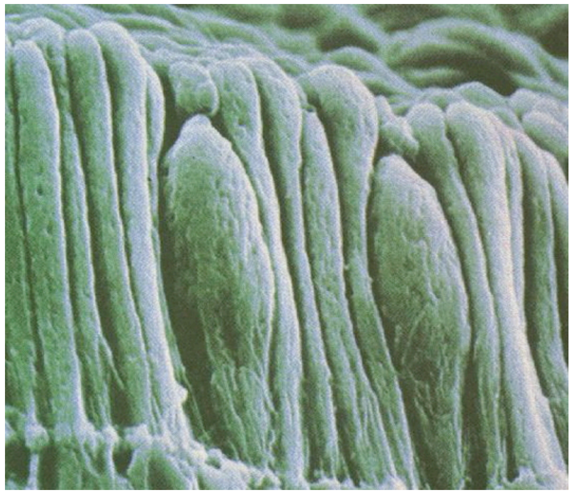
In the chapters on radioactivity, I said that x-rays and gamma rays are also light. They have very short wavelength, way off to the left of the chart. The wavelength of a 100 keV x-ray is about 0.01 nm and of a 1 MeV gamma ray is about 10^{-3} nm (10^{-12} meters). Their frequencies are therefore much higher than that of visible light.

Radio waves and microwaves are also light. They are far off to the right on the color chart – on the long wavelength side. A typical wavelength for a TV broadcast signal is 3 meters. That means that its frequency is $c/f = 3\text{x}10^8/3 = 10^8$ Hz = 100 MHz. The figure has its lower axis labeled in nanometers – and 3 meters is 3 billion nanometers.

Color sensors in the eye

Look at the figure again. It contains all the colors of the rainbow. Do you notice that some "colors" are missing? Where is magenta, or cyan? And, of course, white is missing. It turns out that none of these are pure colors, but are mixtures of colors, in the same way that you get a mixture of notes if you hit several keys of the piano at the same time.

Many animals do not sense color. They can only see that something is brighter or dimmer. This is sometimes described by saying that they see "in black and white" – but grey too. Humans can sense color, but even our ability is very limited. Our eyes have four kinds of sensors. The ones we call **rods** are also found in most animals. Rods sense brightness, but not color. The ones we call **cones** come in three varieties: red, green, and blue. An electron microscope image of the rods and cones is shown in the image below. The thin narrow cells are the rods and the bulbous ones are the cones.



(borrowed from www.eyedesignbook.com/ ch3/eyech3-i.html)

The range of sensitivity for each of the cones is shown in the diagram below.

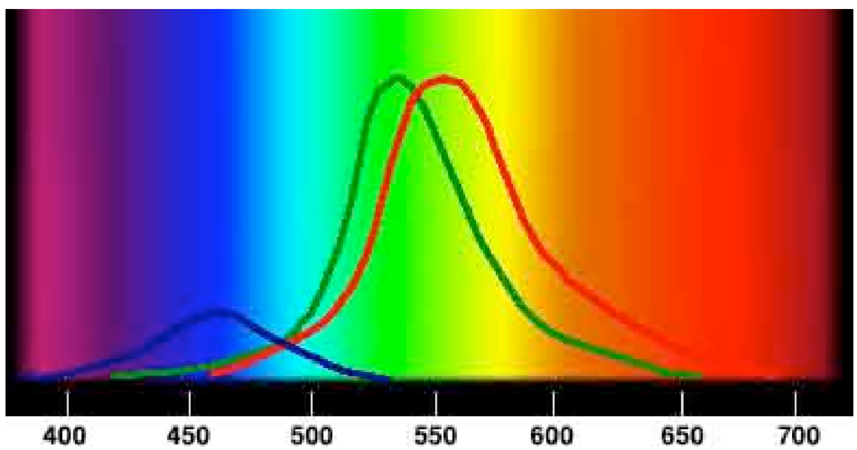


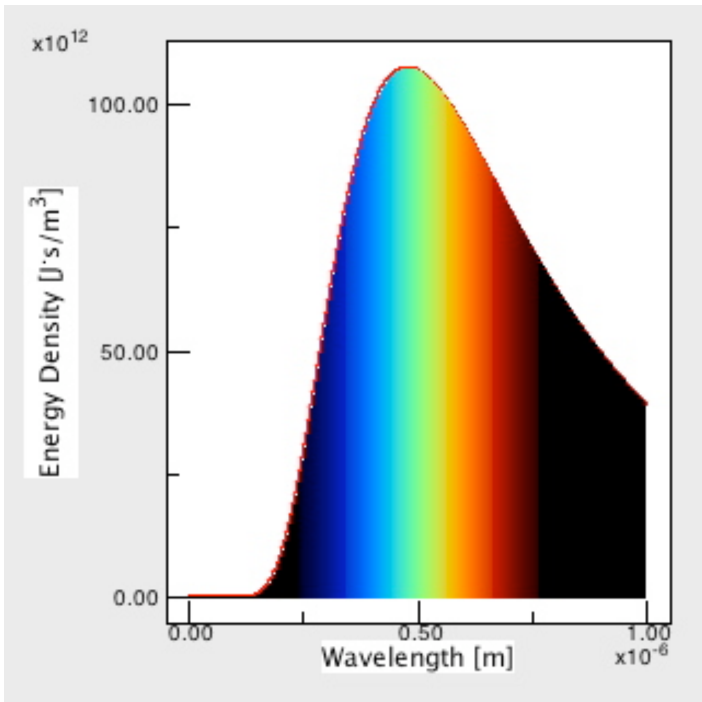
Figure: the sensitivities of the blue, green, and red cones. The blue peaks near 450 nm, the green near 525, and the red near 550.

Notice that the red cone has its maximum sensitivity to green light, not to red! (Remember this! It might be useful on a pop quiz.) In fact, the red cone sensitivity is remarkably similar to that of the green cone. So how does the eye distinguish red from green? Think about it for a moment. Can you figure it out?

The answer is that the eye gets signals from both the green and the red sensors. If the signal from the green cone is stronger, it calls the signal green. Look again at the diagram. To call a signal red, the signal from the red sensor has to be twice as strong as the signal from the green. Only in the red region is the red line twice as high as the green line.

Notice also that green light is detected by all three cones: most strongly by the green cones, a bit weaker by the red cones, and weakest of all by the blue cones. When the brain gets this combination of signals, it calls the color as green. If it receives a strong red, a weaker green, and no blue at all, then it tells you the color is yellow. (Can you see that in the diagram?)

Suppose all three sensors receive strong signals. Then our eye interprets that as "white." In the diagram below I show the intensity of different colors emitted by the sun. When the three sensors of the eye see this, it appears white.



The colors emitted by the Sun, also known as "white" light. The top of the curve indicates the relative brightness of the different wavelengths.

This is not the only combination of color that appears white. Any combination of colors that stimulates the red, green, and blue cones in the same way will give the sensation of white. Since the eye has only three color sensors, it is easily fooled.

The easiest way to fool the eye is by using color dots. Find a white part of a computer screen, and look at it closely. Use a magnifying glass, or if you are nearsighted take off your glasses and look very close. You'll see that, up close, the white isn't white at all, but consists of little red, green, and blue spots. Unlike natural sunlight, the computer screen has no pure yellow, no orange, no blue-green, yet your eye, with its limited ability to discern the different components, can not distinguish it from true white. You eye was fooled by a computer system that adjusts the three colors to stimulate the blue, green, and red cones in just the right amount to make your brain think it is seeing white light. If this is done well, your eye can't distinguish between this "false" white and pure white sunlight.

color blindness

Are you color blind? About 5% of males and 0.5% of females do not have both red and green sensors. (In a class of 200 students, that means 5 males and half a female, on average.) They are called "color blind" even though they can see many colors. But they usually cannot distinguish red from green. That's because with just two sensors (say, for example, the blue and green sensors) light in the green-red region is not detected by the blue sensor. With only one signal, not a ratio, the brain can't guess what frequency the light is.

Have there been any great painters who are known to be colorblind? Would you want to have a colorblind person design the colors for your house? Or chose a shirt for you to wear?

we are all colorblind – multispectral cameras

Suppose you had four different color cones in your eyes, instead of just three. Then an amazing thing would happen: things that used to look like they were the same color, would now be different -- just as red and green are different to the non-color-blind person, but are indistinguishable to someone who is color blind. The white of a piece of paper illuminated by sunlight would appear different from the white of a computer screen. That's because the three colors on the computer screen can only fool three cones. To fool four cones, you would need four colors of dots on the screen.

Cameras are built these days that do exactly this. They can have ten, a hundred, or even a thousand different color sensitivities. Two fields which look like they are identical shades of green, to us, look different to them. They can use this multiple-color ability to detect things that we miss, such as disease in crops, or to identify different kinds of rocks. These systems are called **multispectral cameras**. Multispectral cameras flown in satellites are available, for a price, to photograph and analyze your farm. They are being used by wineries in California to detect the effects of sharpshooter beetles on the vineyards. They will be an even more important technology in the future as we learn to notice patterns and identify the meaning of many multispectral colors. Right now, we are not very good at this because so much of our own color experience is based on just three colors.

So, in a sense we are all colorblind. People called colorblind are really just a little more colorblind than the rest of us. But if we had four cones – blue, green, yellow, and red – what would the world look like?

A discussion topic with no answer

Does a colorblind person perceive red as red, and green as red, or does he perceive red as green, and green as green? Think about it.

Does the question make any sense? Can it be answered? Is it a question in the realm of physics, or isn't it?

Many scientists would say the question is meaningless. We can measure which regions of the brain are stimulated by different colors. But that doesn't answer the question about the colorblind person. Does he see red or green?

Here is my opinion. I believe that we can not answer the question. There is no way to find out the answer. In principle, it cannot be answered.

Many scientists are fond of saying that if there is no way to answer a question, even in principle, then the question is meaningless. Do you agree?

printed color

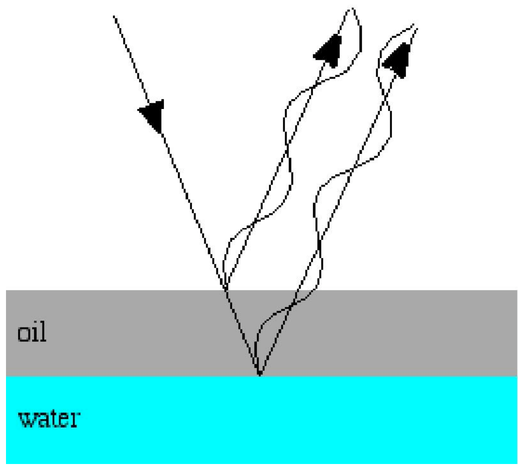
Printed colors work in a similar way to computer screens, but because the inks are usually laid on top of each other, the colors used have to be different. That's because the colors in the ink absorb rather than emit, so they are taking the light away from the reflected light. The colors needed for this are cyan, magenta, and yellow. These are the colors that you used with crayons on white paper. Cyan dye absorbs all light except cyan; that's why cyan is reflected off the paper. For black, you would have to have all three colors laid down on white paper, and it is cheaper and easier to just use a fourth ink colored black. That is the fourth color in four-color printing. Most magazines uses four-color processes. Look at some color magazine photos with a magnifying glass.

But people often don't look at magazines in white light. Fluorescent lights typically have more blue in them than sunlight, and that affect the colors perceived by the eye. Some printing processes use more than the standard four colors in an attempt to achieve the right effect under different lighting conditions.

Colors of an oil slick

The fact that light is a wave is demonstrated by the fact that two light waves can cancel and reinforce. Such cancellation is the cause of the colors seen on a thin film of soap. Another way to see the cancellation is in an oil slick.

Since oil is less dense than water, a few drops of oil will float on the surface. As they spread out, they can make a very thin layer. In fact, it is common for that layer to be only a few microns thick, comparable to the wavelength of light. That fact enables us to notice the cancellation of light waves. Look at the diagram below, which represents the cross-section (viewed from the side) of a greatly magnified oil slick:



The light enters on the left side. I've shown its direction by the line; I haven't shown the individual oscillations. Some of it reflects off the top of the oil, and an equal amount reflects off the top of the water. (Some light continues to penetrate the water, but we don't show that.) There are two reflected waves. The two waves will overlap. For the reflected waves, I've drawn the oscillations. Note that I've drawn them so that they approximately cancel. When this happens, the total wave reflected is zero.

If the wavelength of the incoming light were different (but the thickness of the oil layer were the same), then the two waves might reinforce rather than cancel. In fact, white light is full of waves of different colors. Some cancel, some reinforce. The ones that reinforce are the ones we see in the reflected light. Since the thickness of the oil slick is different at different locations, the colors that reinforce are different at different locations, and that is what gives rise to the large variation in colors from an oil slick.

Most people think an oil slick is ugly. That's because they associate them with pollution, such as spilled oil, or decaying vegetable matter in a lake. But when I see an oil slick, I think that Newton, if he had been clever enough, would have recognized from the colors that light must be a wave.

Images

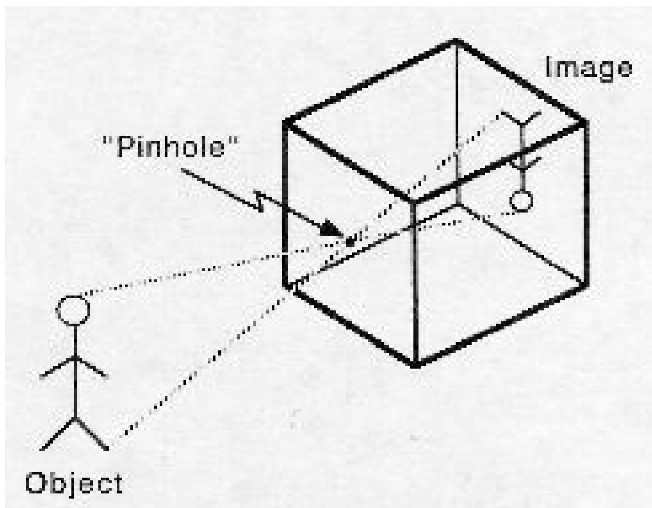
Of course, the most remarkable feature of light is that we use it to see. The eye manages to give us amazing detail about objects, even ones that are far away. This is done by the fact that we can create an "image" of an object in our eye. The concept of image is also critical for understanding holograms, mirrors, cameras, microscopes and telescopes.

We'll begin with the simplest device that can create an image.

Pinhole camera[6]

This is the simplest kind of camera anyone has ever used. It makes use of the fact that light travels in straight lines, more or less. It does that only because its wavelength is so short, that a packet of light behaves very similar to the way a particle would behave.

A pinhole camera consists of a box with a small hole on one side. Light from the object passes through that hole, and lands on the back. In the diagram, you see that light from the head region lands low on the back, and light from the feet lands high. If you were to look at the back you would see an "image" of the object. Note that the image is inverted, compared to the object.



You can make a pinhole camera, using any box, a small hole, and a piece of paper for the back. If the pinhole is too large, the image gets blurry. That's because light from several places on the object can reach the same place on the paper. If the pinhole is too small, then the image is very dim and hard to see. It works best with "waxed paper" (available in supermarkets – it was a predecessor to plastic wrap) rather than ordinary paper, since waxed paper transmits the light better, so you can see the image through it.

A camera works in exactly the same way, except that the pinhole is replaced by a lens, and the paper replaced by something that records the light. We'll discuss lenses in a moment; their main advantage is that they let more light in than does the pinhole.

brief history of photography

If the image makes a permanent change on the material placed on the back of the camera, then we have created a *photograph*. This was originally done with chemicals on a plate placed in that position. The first known photograph was taken by Joseph Niepce in 1827.

[6] Some people claim that the Pinhole camera was invented in Pinole, California, and that's where the name came from, but I don't believe that.

He used a chemical called bitumen that hardened when light hit it. If he then washed away all the soft material, he was left with a thin sculpture that resembled the object (e.g. a person's face) that was preserved. At the time, even this crude image was hailed as a miracle of technology, since the only other way to capture someone's face was by hiring an artist, or by tracing a shadow. Most people thought the captured image was remarkably realistic, even though it was very crude by today's standards.

Louis Jacques Daguerre improved on this with metal plates. His artistic ability was also extraordinary, and many of his Daguerreotypes have become famous. The plates were improved by Talbot and Eastman, who used silver halide. The silver halide breaks up when exposed to light, and the silver particles are released. The process of "developing" the plate consists, first, of removing the unexposed silver halide, and then reversing the exposure. (The silver particles give a black appearance, and yet they were exposed to light. So a second image must be made to reverse the process and give a realistic black-gray-white image.)

In the 20th century, the photographic plates were replaced by flexible photographic film that was coated with the same chemicals. Photographic film (or just *film* for short) became one of the major uses for silver! I wouldn't invest in silver today, since digital cameras may soon make silver superfluous, and then we may have an excess.

more on pinhole cameras

You can actually build a pinhole camera and take photographs using ordinary photographic film. There are clubs that do this. Not surprisingly, there is even a website that sells pinhole cameras: www.pinholecamera.com. Of course, you could make one yourself very easily, since nothing special is needed. The hardest part is keeping stray light away from the film, so that the only light that reaches it is through the pinhole. The pinhole doesn't let in much light, so long exposures are needed.

If you use a larger pinhole, then the exposure can be shortened. But a larger pinhole means that the light from any point on the object gets spread over a region of the film that is as large as the pinhole (or even slightly larger). This makes the image blurry. So when taking a pinhole picture, you have to decide how long you can hold the camera (a shaky camera also blurs the picture) and how big a hole you can use.

I show a class pinhole camera demonstration with several different pinhole sizes. You will note that when the pinhole size is made larger, that the image stays the same size, gets brighter, but more blurred.

Eyes

Your eye acts very much like a pinhole camera. The "pupil" acts like the pinhole, and the retina (with its rods and cones) acts like the film. Each sensor sends a signal to the brain, which then interprets the image.

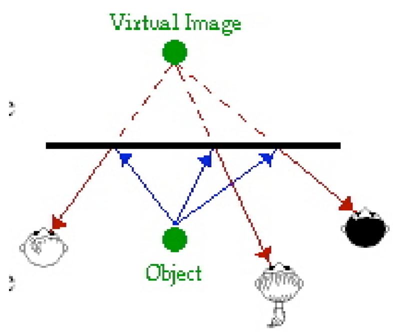
In fact, the eye uses a lens just behind the pupil, to focus the light better than the pupil would by itself. We'll discuss lenses soon.

But here is the key thing I want you to recognize: the eye is a device for measuring the brightness and color of light for different directions. That's is a simple statement, but ponder it. You eye tells you, for every direction in its field of view, the color and brightness of the light coming from that direction. This is all that an eye measures.

When looking at a three color computer screen, the eye is fooled into thinking that equal mixtures of red, green, and blue make white. But there is an even more marvelous way to fool the eye. It is called a *mirror*. It fools the eye into thinking an object exists, where it doesn't.

Mirrors

Mirrors are wonderful miracles that we pay little attention to since they are so common. A mirror is a surface that is very good at reflecting light. When our eye sees light coming into it, it has no way of knowing if the light is coming directly from an object, or is being bounced off a mirror. The spot behind the mirror from which the light appears to be coming is also called an image, even though it is quite different from the pinhole camera image. Here is the key difference: there is actually no light present at the image location. You can see that in the following diagram:



Flat mirror. Figure borrowed from
http://www.glenbrook.k12.il.us/gbssci/phys/Class/refln/u13l2b.html

Study the figure. Light from the object bounces off the mirror, and into the eyes of the three people shown. Notice that they all see the light exactly the same way that they would see it if no mirror were present, but instead the light was coming from the location marked "Virtual Image." That's what makes the image from a mirror so compelling. Even if you move your head around to different locations, the position of the image doesn't change its location. The image behaves just like a real object. But note that there is no light passing through it. That's why it is called a *virtual* image.

mirrors and magic

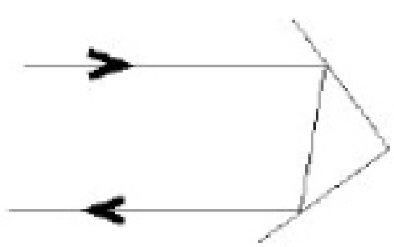
We take mirrors for granted because high quality mirrors are so abundant in modern society. And yet we can still be fooled by them. They are favorites of magicians, and of those who create illusions at places such as Disneyland. Suppose you want to make it look like a ghost is sitting next to a visitor. (This is done in the haunted house of Disneyland.) The trick is to use a "half silvered" mirror, a mirror that reflects half of the incident light, and transmits half.

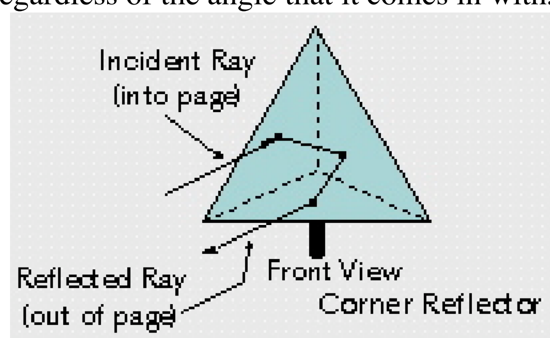
If you look in such a mirror, you'll see your own reflection, but you'll also see transmitted light. If the object behind the mirror is made to look like a ghost, you'll see you own reflection, and what appears to be the reflection of a ghost sitting right next to you. The ghost will disappear as soon as the light shining on the ghost model (behind the mirror) is extinguished.

So this illusion is taking advantage of the fact that we are so accustomed to mirrors, that when we see someone in the mirror that looks like us, we assume that all the light is being reflected. The illusion would not work on someone who had never seen a mirror.

Corner reflector

When light bounces into a corner, with each wall a mirror, then it returns in a path parallel to the path in. This is easiest to see if it hits only two mirrors, and I show that in the left diagram below. For those of you who enjoyed geometry, I leave it as an exercise to show that if the mirrors form a right angle with each other, that the returning light will be parallel to the incoming light, regardless of the angle that it comes in with.





(2nd image borrowed from:
www.its.bldrdoc.gov/fs-1037/ dir-009/_1298.htm)

The diagram on the right shows what happens when light hits a corner in which three mirrors come together. Just as with the first diagram, the light bounces back in exactly the same direction that it came from (but shifted to the side). I show in class a demo of corner reflectors in which I shine a laser beam on a mirrored corner, and the beam comes right back at me, displaced sideways by a little bit.

If you throw a frictionless ball against the corner of a room, the ball will come right back at you. This would be useful knowledge for certain indoor sports, including racquetball and squash, except for the fact that the balls in such sports have significant friction, and when the balls spin, they bounce at different angles, and so the corner reflection rule (that the direction of rebound is parallel to the incident direction) fails.

There are optical devices other than corners that do the same thing, i.e. reflect light back in the direction of the source. The general term for such an object is a ***retroreflector***. I'll show later that cameras and eyes are retroreflectors, and that accounts for the annoying artifact in photographs known as red-eye.

corner reflectors on the moon

In the 1970s, an experiment was done to bounce light from the Earth off the moon. A powerful laser was used to shine light on a small spot, and the spot was observed with a telescope. To make sure that as much light as possible came back towards the telescope, the astronauts placed corner reflectors at their landing site. From the time it took the light to go both ways, scientists were able to measure the distance to the moon to an accuracy of a few centimeters. That precise measurement may sound silly, but by using this extreme accuracy as the Moon went around the Earth, we were able to detect the very small changes in the orbit that are predicted from Einstein's General Theory of Relativity.

corner reflectors for radar

Radar is a form of light (electromagnetic wave) but with a lower frequency and much longer wavelength than visible light. A typical radar wavelength is 1 cm to 1 meter (vs. 5 $x10^{-5}$ cm for visible light).

You can make corner reflectors for radar too. Ordinary metal works well; there is no need to polish the metal to "mirror-like" shine since the wavelength is so much longer.

Corner reflectors are extensively used in radar. For example, if you are flying an airplane using radar for navigation, a corner reflector placed near an airport runway can help you locate it. As you point your radar emitter in many different directions, there will be only one direction in which the radar comes right back – when it is aimed at the corner reflector. Radar corner reflectors on boats or hung from balloons can make it easy for radar to locate them. Project Mogul (Chapter 7) had corner reflectors hanging from the balloon, so that people on the ground using radar could tell precisely where each flying disk was located. Such information was needed in order to deduce the direction to the Soviet nuclear bomb tests.

Stealth

In radar, the radio receiver emits a strong signal, and picks up the reflection. If there is a corner on the target, then the signal returned will be very large. If you don't want to be detected by radar, then you should not have any right angles on your object. If you look at modern military stealth aircraft, you'll notice that they don't have right angles. Even the tail is tilted with respect to the wings, so a right angle doesn't form. This is all part of the "stealth" technology. Don't have any inadvertent corner reflectors!

The other trick to stealth is to cover the airplane with material that absorbs the radar, rather than reflects it. Such materials are called "black to radar." That is using the word black as a metaphor for something that does not reflect. An object is black if it doesn't reflect visible light. But no material can be made completely black. If it could, then the absence of corner reflectors would not be necessary.

Slow Light

Light does not always travel at the speed of light. That paradoxical statement was purposely worded to be confusing, so that you will remember it. So let me explain to you what I really mean.

When scientists use the term, "the speed of light", we usually mean the speed of light in *space*, denoted by the letter "c", and which is approximately 186,242 miles per second. That's fast enough to get to the moon in about 1.3 seconds. This speed is also equal to 300,000 km/sec, and to 1 foot per nanosecond. (Recall, a nanosecond is one billionth of a second, about the time it takes your computer to make a computation.)

But that is only the speed of light when it is traveling in a vacuum. When light enters materials, it travels at a slower speed. In the air, it travels at about 99.97% of c. In water, light travels at only 75% of c! In glass, it travels even slower, at about 2/3 c. That's still pretty fast, of course. But it is not as fast as the speed of light in vacuum. In some exotic materials, physicists have managed to have the speed of light come down close to zero.

The quantity c is not only the speed of light in vacuum, but it is also the speed of gravity waves, and the speed of anything that has zero rest mass. We'll talk more about that when we discuss relativity theory. Perhaps a better name for c would be "the velocity constant from relativity theory." Or it might be called "the speed in vacuum of massless particles." But, for purely historical reasons, it is usually referred to as the "speed of light." Just remember, the actual speed of light when it goes through materials is not always c.

If neutrinos had been discovered before light, we might have used the term "speed of neutrinos" instead of "speed of light." For many decades we believed that neutrinos had zero mass. But evidence published recently suggests that some neutrinos actually have a tiny but non-zero mass. We know that there are three kinds of neutrinos, which we call the *electron neutrino*, the *muon neutrino*, and the *tau neutrino*. It is still possible that the electron neutrino actually is massless, but we can't really be sure of that.

Now that we know that some neutrinos have mass, it is reasonable to ask whether particles of light have mass. (As we will see, quantum mechanics says every wave is also a particle, and the particle associated with light is called a photon.) We think … that light particles probably do *not* have mass. We do know that if they do have mass, it is much smaller than the mass of any other particle.

The index of refraction "n"

The speed of light in different materials, such as glass or water, can be described by its value compared to the speed of light in a vacuum. The "index of refraction" n is defined as:

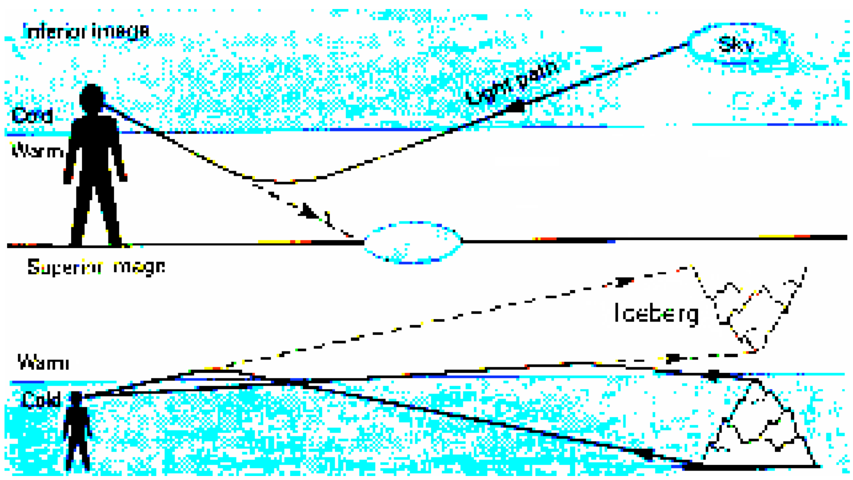
$$\mathbf{n = c/v}$$

From this, you see that the speed of light in a material that has index n is given by v = c/n. The index of refraction of sea-level air is about 1.0003, so the speed of light in air is c/1.0003 = 0.9997 c. The index of refraction for water is about 1.33, and for glass is about 1.5. So in glass, v = c/1.5 = (2/3) c. In glass, light travels at 2/3 its speed in vacuum.

Mirages

On a hot day, when you look along a road, you sometimes see what appears to be a puddle of water on the road. In the desert, you see what looks like a lake along the horizon. But it isn't there; it is an optical illusion called a mirage.

Remember how sound was bent by air? When the ground was warm, sound tended to bend away from the ground; when the ground was cool, sound tended to bend towards it. Exactly the same phenomenon occurs with light. When the air is hot (e.g. above a hot road) then the speed of light is faster than in cold air. The result is that light will tend to bend upward. Blue light from the sky can be bent upward in this way, and give the illusion that the blue light is coming from the ground, i.e. from a pool of water. A diagram illustrating this is shown in the upper half of the figure shown below. The light ray bends, but your eye doesn't know that. So you assume that the blue is coming from the ground; you interpret this as a puddle of water.



(borrowed from http://www.triviaplanet.com/did%20u%20wonder/scienceandtechnology/mirage.html)

The second half of that figure shows how a mirage can also make it look as if there is an upside-down mountain up in the sky. That's because when you look upward, you see the light coming from the mountain. This kind of inverted mirage is common in the far North, where Aleut kayakers can spot distant land and ice flows by looking towards the sky.

Splitting the Red Sea

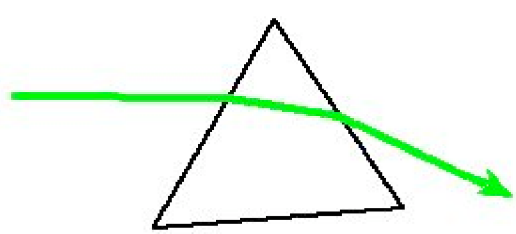
According to the Jewish/Christian Bible, Moses invoked the power of God to push aside the waters of the Red Sea, in order to allow the Jews to escape from Egypt. Another possible interpretation is that the ancient Jews assumed that Moses had split the sea but had been fooled by a mirage. If you are interested in reading part of a chapter of a novel that describes this possibility, then go to the selection of the novel. This reading is definitely *NOT* required! I warn you: it is written in the first person by the character Jesus, who has been enslaved. If that offends you, don't read it. In the excerpt, his good friend and mentor, Simon, gives him a lesson about how people fool themselves.

Diamonds, dispersion, and fire

When light enters a diamond, unless it hits exactly perpendicular to the surface, it bends. This happens because the part of the light wave that hits the diamond first is slowed, and the rest of the light is bent in that direction.

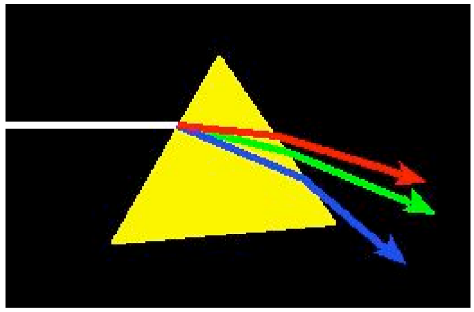
The bending is exactly the same effect that we had in the mirage, and it is completely analogous to the bending of sound that we had in the sound channel, and in hearing distant sounds in the evening. Light bends towards the direction in which it is traveling more slowly. The only difference here is that the diamond has a surface, so the light enters it suddenly. But the bending is exactly the same as when light enters a region of air that has a different index of refraction.

This is illustrated in the diagram below. The index of refraction of a diamond is 2.4, so the speed of light in a diamond is c/2.4.Green light enters the triangular piece of diamond, and is bent. Note that on entering, it is bent towards the diamond, and again on leaving. Both times, it bends towards the right, since that is the side in which light travels more slowly. It is the right side of the narrow beam that enters the diamond first.



Do all colors of light bend the same amount? The answer is: approximately but not exactly. The speed of light depends on frequency, i.e. on color, so different colors bend different amounts. This effect is called ***dispersion*** since it means that white light is separated (dispersed) into different colors. This is what gives rise to the many different colors, and that's what makes the diamond so beautiful.

Dispersion is illustrated in the diagram below. Now I have a white beam coming in from the left side and hitting a triangular piece of glass called a prism. I've put everything over a black background. For this diagram, the glass is colored yellow.



The fact that the three colors are separated is simply a result of the fact that in glass (or in a diamond) the three colors all move at slightly different velocities. So red, green, and blue light do not have exactly the same index of refraction -- they are a tiny bit different. The index of refraction for a material such as diamond, when listed in a table, is usually given for a middle color (yellow), and the dispersion number is the difference between the indices of refraction for blue and red. In the gem business, dispersion is called "fire". A gem with high dispersion has strong fire.

When people looked through a prism at other people, they could see them, but they seemed to be surrounded by an aura or halo of colored light. There are glasses you can buy today at novelty stores that do the same thing. The ghost-like colors that surrounded people were called "spectra" – meaning ghosts. Even today when a scientist makes careful measurements of the different frequencies present in a beam of light, the terminology persists: he says he is measuring *spectra*.

Here, for example (you are not required to know these numbers!) are the indices of refraction for ordinary glass, for water, and for diamond:

	glass	**water**	**diamond**	**cubic zirconia**
red	1.514	1.331	2.410	2.22
yellow	1.517	1.333	2.417	2.23
blue	1.523	1.340	2.450	2.28

From the table, you can see that the dispersion for glass (n_{blue} minus n_{red}) is 1.523-1.514 = 0.009. The dispersion for water is the same: 1.340-1.331 = 0.009. But the dispersion for diamond is 1.450 - 1.410 = 0.040. That is more than four times greater than for water or glass! It is this high value of the dispersion that gives diamond its "brilliance", i.e. the fact that it appears to "sparkle" with different colors when you move it slightly.

counterfeit diamonds – and advice for the engaged

Cubic zirconia, called CZ for short, is a man-made crystal that is much cheaper than diamond, but has even more fire. It is often sold under the name of "counterfeit diamond." Look it up on the web. Whereas the dispersion (fire) for diamond is 0.040, the dispersion for CZ is in the range 0.060 to 0.066. Because of this high dispersion, in sunlight it glitters with significantly more color than does diamond. Since it is primarily such *fire* that made diamonds so desirable, that means that CZ is more beautiful than diamond, at least according to the traditional evaluation.

It is also much much cheaper. Gem quality diamonds cost about $30,000 per gram, or about $6,000 per carat. One carat of CZ costs about $20. (See, for example, http://e14k.com/czinfo.htm.) Wow! Greater beauty, at 1/300 the cost! Different processes produce CZ with different dispersions. The range is 0.060 to 0.066. Which value of dispersion would you guess is the most valued? The one with the most fire, the most beauty, i.e. 0.066?

Nope. Most people prefer the lower value. Why? Can you guess?

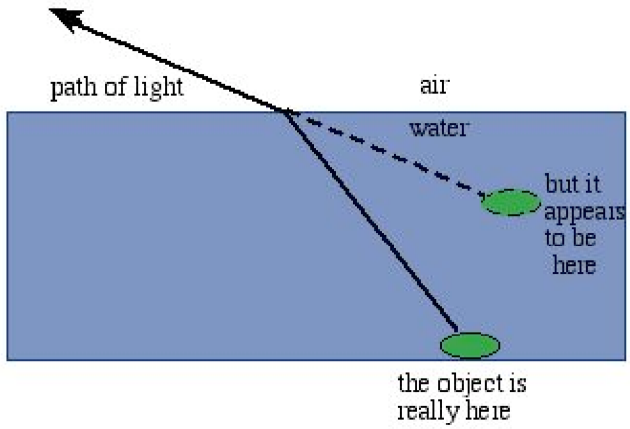
Here is the fascinating answer: people prefer the smaller dispersion, and its lesser fire, because it looks more like a "genuine" diamond! Many people don't like CZ that sparkles too much, because then everyone knows it isn't diamond. The irony is that the diamond was initially admired because it had more dispersion than any other gemstone. It was also very expensive. Now we have something that is prettier, but inexpensive, so many people don't want it. How can you show someone that you love her/him by giving them something beautiful but cheap? Diamonds are admired because they are expensive, and they are expensive because they are admired. Put another way, diamond is expensive because it costs so much. Some day I predict the price of diamonds will plummet because their value has no real basis.[7]

So, when you get engaged, save money: get the prettier stone, and save a fortune, and laugh at all those who waste money enriching the de Beers diamond cartel, and send me a card telling me that you took my advice!

Swimming pools, spearing fish, and milk glasses

Because water has an index of refraction of 1.33, light leaving the surface is bent, and that gives rise to many illusions. One of the strangest of these is the swimming pool illusion: when observed from an angle, the pool appears to be much less deep than it really is. We can see why in the diagram below. Light from an object on the bottom of the pool is bent as it emerges from the surface (note: it is bent *towards* the water), and this makes it look as if the object on the bottom is not as deep as it really is.

[7] Unless you value a diamond because it is the hardest known material. But that is not a very romantic feature.



When you look at your friend, who is standing just a few feet from you, the effect can be comical, since his feet might appear to be only a short distance below his head.

The effect also causes potential problems for people who are, for example, trying to catch fish. Suppose you have been trapped on a remote island, and are trying to survive by throwing a spear at a fish. (This happened in the recent movie "Cast Away".) Look at the diagram above. Let the green object be the fish. Where should you aim? Above, or below the apparent location of the fish?

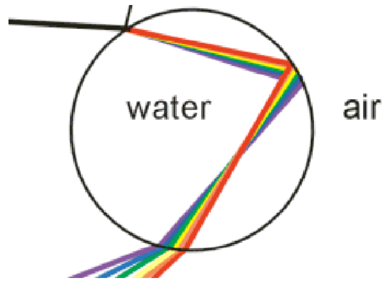
The answer is: aim below. The fish will appear to be shallow, but it is in fact deeper. Don't aim at the location where it appears to be.

The same phenomenon occurs with milk glasses, but sideways. Take a round glass and fill it with milk. Now look at the side of the glass. Do you notice how the milk seems to come right out to the edge of the glass, as if the glass had zero thickness? This can be explained by the same diagram above. The "object" is now the milk. The "depth" of the object is now the thickness of the glass. But the light, when it hits the surface, bends towards the glass. So someone looking at the white light from the milk sees it at a grazing angle, as if the milk is really much closer to the outside of the glass than it really is.

Rainbows

Dispersion in water droplets is responsible for one of the most beautiful of natural phenomena, the rainbow. Rainbows are actually much harder to understand than you might guess. Any time you are looking at a rainbow, you are actually looking at small round droplets of water, and the sun is behind you. The water could be the spray from a waterfall, from a sprinkler, droplets of fog, or rain from a cloud that you don't even notice. Whenever it has been raining, and the storm moves away, and the sun comes out, Look for a rainbow on the side opposite you from the sun. If rain is still falling over there, then you should see a rainbow.

Small raindrops are spherical, and when enters the front surface, it bends, bounces off the back, and then comes out. The path is shown below:



Actually, some of the light leaves the back side, but that isn't shown in the diagram since it doesn't contribute to the rainbow. You can see how the different colors bend and separate whenever they pass through a surface. (I exaggerated the separation.) But how does this pattern of separation lead to the rainbow?

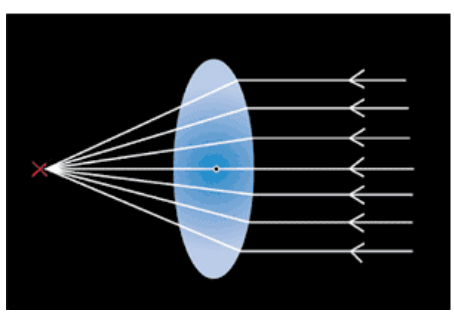
Notice the emerging light. It is going in a particular direction. Unless there is a person standing in that direction, there will be nobody to see the color. Someone standing directly to the left of the droplet will get no reflected light (except a little off the surface.) Every drop spreads its colors out, but only certain drops send light in the right way to reach any particular person. Those are the drops that appear colored, and make up the rainbow. For each drop, only one color bends at the right angle to reach the person who is looking. If the person is standing in the path of the blue ray, then the drop will appear blue. The red light will miss his eye; it will pass below his eye. (Can you see that in the diagram? The red light comes out lower than the blue light.)

There will be some drops that are high enough above the blue drops, that the red light coming from them will hit the observer's eye. These drops will look red to the observer. They won't look blue, because for these drops, the blue light passes above his head.

(Some day I hope to add a diagram here illustrating this.)

Lenses

A lens is a wonderful invention that takes spread-out light coming from one source and focuses it all to one spot. It does this by having a curved surface, so the light at the edges bends more than the light in the center, as in the following diagram.

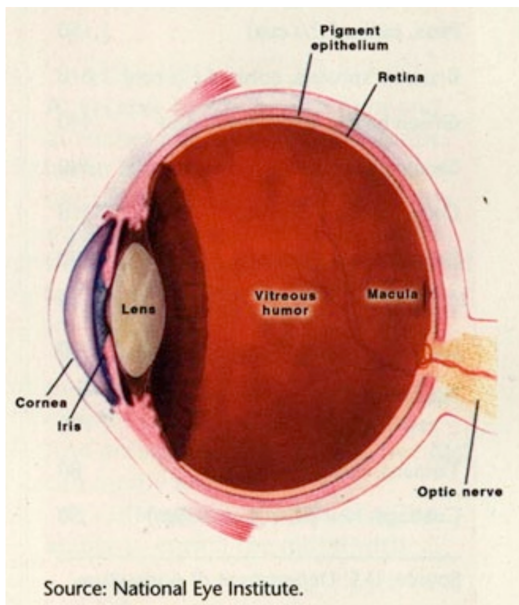


(borrowed from
ebiomedia.com/gall/eyes/images/ lensRefractBlack300.gif)

The marvelous thing about a lens is that it takes light that is spread out and brings it to a point. That's why it can be used to concentrate sunlight, and start a fire. But it is also the reason that the pupil of our eyes can be larger than a pinhole. If we widen the pinhole opening in the pinhole camera, the image gets blurred. But if I put a lens in the wide opening, the broad beam of light is brought to a small focus. That way I can let in a lot of light, yet still get and a non-blurred image. Otherwise, the camera – or eye – works the same way as a pinhole camera.

Eyes

The human eye actually has two lenses. One is called, appropriately, the "lens." The other is called the cornea. These are shown in the diagram below. The iris is the pretty part of the eye, the colored part that opens or closes to let more or less light in.



Source: National Eye Institute.

The cornea does most of the focusing. But the lens is variable. If squeezed by the muscles of the eye, it can change the amount it focuses.

The variable lens

Why should we need a lens of variable strength? The reason is that nearby objects need more focusing than do distant objects. If you are looking at a flower, and it is close to your eye, then the light from each petals is spreading out slightly by the time it reaches your eye. If it is to be brought to a good focus on the back of your eye, such light has to be bent more than, say, the nearly parallel light from a distant star. This process of squeezing the lens to make it accommodate far away objects is called "accommodation."

nearsighted

If your cornea is too curved (or if the retina is too far back) then it is easier to focus on nearby objects, but hard or impossible to focus on distant objects. When that happens we say the person is nearsighted. That can be fixed by reshaping the cornea so it doesn't focus as much. (That's what Lasik surgery does.) Or, if you don't want someone to carve away at your eye, you can wear contact lenses or eye glasses.

There is speculation that some people become nearsighted by doing a lot of reading when young. This could conceivably come about by the continual squeezing of the lens, until it begins to keep the squeezed shape. But most experts dispute this process and say it doesn't happen. It is just as plausible that children who are naturally nearsighted find reading to be less stressful on their eyes than children whose eyesight is "normal."

farsighted – and aging

As you grow older, the flexibility of your lens is lost. Eventually you cannot squeeze your lens enough to be able to focus on nearby objects. (There is an exception. Some people were nearsighted as they aged, and when they lose their accommodation, they focus only on nearby objects.)

Everyone loses their accommodation as they age (the process begins when we are very young), and so all of us (except those who are already nearsighted) eventually become farsighted, usually by the age of 40. Some older people claim to be able to see both near and far, but that invariably means that they have one nearsighted eye and one farsighted one.

People who are over age 35 cannot squeeze their lens enough to focus over the whole range desired distances. Typically, they might wear bifocal lenses in their eyeglasses. Bifocals are really just two lenses of different strength placed one above the other. The person wearing them uses the lower, stronger lens for reading, and the upper weaker lens for more distant objects.

When you get to age 35, you might consider buying "reading glasses." These are inexpensive ($10), and available at most drugstores. Sometimes they are half lenses so the reader can look over them when he wants to see something that is further away than the book. People who wear such half lenses are readily identified as age 35 or older.

Since only older people wear bifocals, those who want to "look young" don't want to wear them. Eyeglass makers go to great extremes to conceal the fact that eyeglasses are bifocal by hiding the line that divides the two lenses.

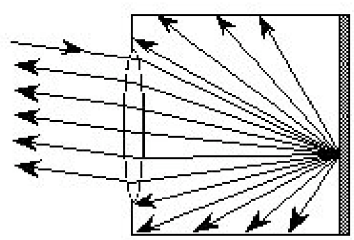
On the other hand, actors can look older by wearing half lenses, or by picking up a newspaper and holding it away from them – indicating that they are farsighted, and therefore older. It is interesting that even young people recognize that behavior, even if they don't realize why the person looks older. If you see only older people acting that way, then you begin to associate the behavior with age.

Another way to avoid the "old" look of bifocals is to have two different lenses for your two eyes, one which focuses near and the other far. Then you can pretend to be younger than you are. This is what "bifocal contacts" usually mean. No matter what distance you see, it will be with only one eye at a time.

You may find some older people who are proud of the fact that they don't need glasses, even for reading. In every case that has been studied, that has meant that their two eyes are different. One focuses in close (useful for books) and one far away (useful for reading signs).

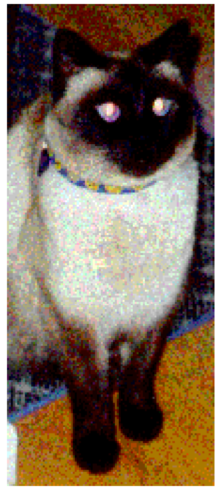
Red eye – and stop signs

The eye also works as a retroreflector, sending a beam of light that hits it back to the source of the light (just as a corner reflector does). This happens because of the focusing property of the eye. Look at the diagram below. The incoming light (arrow coming from left, towards the lens) is focused on the surface at the right.   Some of it bounces, but that bounced light scatters in all directions. But all of the bounced light that hits the lens is deflected to return to the source of the light. You can see that below by the fact that the outcoming light is parallel to the beam of incoming light.

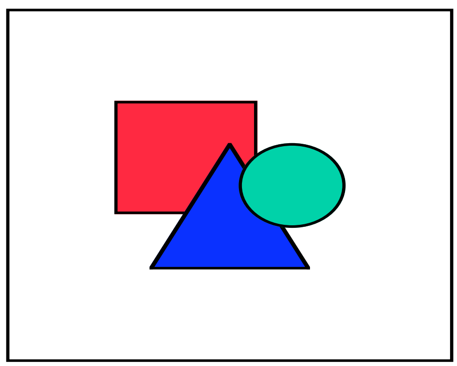


When you take a photograph of a person, much of the light from the flash returns directly to the flash. If the lens of the camera is near the flash, then much of this light goes right back into the lens, creating the ugly phenomena we call "red eye." On the right is a photo of Prof. Stuart Freedman's cat showing the red eye phenomena: The light that enters the pupils of the eyes tends to come right back towards the camera, making the center of the eyes appear bright when they should be dark.

The picture below shows this effect in a flash photograph of a cat. His "red eye" is not very red. In humans, the red eye is usually redder, probably because of the physiology of they human eye; maybe our retinas have more blood.



A small retroreflector can be made from a spherical bead. If the glass is chosen properly, then light hitting the front surface is focused on the back surface; it reflects and it then refracted back to the source as shown:



These beads can be as small as grains of sand, and are now produced very cheaply. If these grains are glued to the surface of a road sign, then they will reflect the light from headlights right back at the car. As a result, they make road signs look very bright to the person in the automobile. Beads such as these are also used to coat surfaces (such as night clothing) that you want to look bright in headlights.

In Yosemite, if you shine a flashlight on a tree that contains a bear, all you will see clearly reflected are the two bright eyes. I'll try to find the photos I took of a bear trying to steal our food, which we had strung up on a tree limb.

microscopes and telescopes

We've learned everything we need to know to understand telescope. In both of these systems, a lens is used to form an image of the object. If the object is far away, we call the system a telescope; if it is small and nearby, the system is a microscope.

Look at the diagram for the pinhole camera again. If the object is very close to the pinhole, then the image will be larger than the object. That's what a microscope does. To be able to look at this image, up close, a second lens is placed in front of the eye. That's caused the ocular.

For a telescope, an image is made of a distant object. That image is usually placed just in front of the eye. It could be put on a translucent screen. Then an "eyepiece" is put in front of the eye so that it can focus up close, and see details of the object. It turns out that the translucent screen is unnecessary. The light forms a focus at the place where the screen would be, and continues on, into the eyepiece.

Keck and Hubble telescopes

In astronomy, the problem is not only magnification, but also collecting enough light to see a dim distant object. That is why most astronomers talk about their telescopes in terms of their diameter. The "most powerful" telescope in the world is the ten-meter telescope at the Keck observatory. It uses a curved mirror to focus light instead of a curved lens. The ten-meters refers to the diameter of the lens, and that means its light collecting power.

Any ground-based telescope suffers from the fact that air pockets form little lenses, and these make continually changing distortions in the focus. That is one of the primary reasons that we put some astronomical telescopes in space. The most important of these is the Hubble telescope. Its diameter is only 2.4 meters, but because it is above the atmospheric distortions, it can focus much better, and see things that are much smaller in their apparent size (e.g. the diameters of distant stars and galaxies) than can ground-based telescopes.

Spreading light – diffraction

Have you noticed that we haven't mentioned the wave nature of light for quite some time? That's because, for much of optics, the only thing we have to know is that light bends when it goes from one substance to another one with different index of refraction, a phenomena that is called ***refraction***.

When making powerful telescopes and microscopes, the wave nature becomes important again. Any wave, when passing through an opening, spreads a little. You can see this when a water wave passes through an opening. If not for such spreading, we usually would not hear people shout when they talk from behind a corner.

There is a simple formula for the spreading of waves. The only thing you need to know is the wavelength of the wave, L, the size of the opening, D, and how far away the opening is, R. Then the wave will spread by a blurring amount

$$B = (L/D)\ R$$

You don't need to learn this formula, but it will be useful for us to calculate the problems with many important optical systems, such as spy satellites. The most surprising thing about this formula is that small wavelength waves spread less (if the wavelength L is small, then the spreading S is small too). That is the reason humans hardly notice spreading for light. For visible light, L is only a half micron, so most of the spreading is negligible. It becomes important only for really small details, since the spreading causes blurring. That happens with telescopes, and for fine detail with cameras.

It turns out that the same equation can be used to determine the closest objects that an optical system (camera, eye, or telescope) can distinguish. That distance B, sometimes called the resolution, is given by the same equation

$$B = (L/D)\ R$$

where B is the separation of the objects (the blur distance or resolution), L is the wavelength, D is the diameter of the lens or opening, and R is the distance to the objects.

Let's now see how this limitation is important for spy satellites.

spy satellites

Suppose we want to put the Hubble Space Telescope in geosynchronous orbit, to observe whatever is happening in the mountains of Iran. We want it to be geosynchronous so that it will always be above the same place. What will we be able to see? Will we be able to recognize people? Can we read license plates? The answer turns out to be no. Diffraction will cause so much blurring that we will not be able to see details that are smaller than 7 meters, or about 23 feet!

Here is the calculation. For geosynchronous orbit, we set R = 22000 miles = 35000 km = $3.5\text{x}10^{7}$ meters. Let the wavelength of light correspond to the value for visible light: 0.5 microns = $5\text{x}10^{-7}$ meters. The diameter of the Hubble telescope is 2.4 meters. So the resolution on the ground will be:

$$\begin{aligned} B = (L/D)\ R &= (5\ \text{x}10^{-7}/2.4)\ 3.5\text{x}10^{7} \\ &= 7 \text{ meters} \\ &= 23 \text{ feet} \end{aligned}$$

So two object on the ground which were separated by 23 feet would be blurred together in the image!

Suppose we put the Keck telescope into geosynchronous orbit? It is about 4 times bigger than the Hubble, so it could do 4 times better, or about 6 feet. Better, but still not very good.

Now let's do the calculation for the Hubble 2.4 meter telescope in LEO (low earth orbit), a height H = 150 miles = 240 km = $2.4\text{x}10^{5}$ meters. The only quantity that we change in the previous calculation is H. So for a low earth orbit we get

$$X = (2 \times 10^{-7})\ H$$
$$= (2 \times 10^{-7})(2.4 \times 10^{5}) = 0.05 \text{ meters}$$
$$= 5 \text{ cm} = 2 \text{ inches}$$

So a low earth satellite could almost read a license plate. But a geosynchronous satellite misses by a big factor, due to wave spreading as the light passes through the aperture of the telescope.

resolution of the human eye

We can use the same equation to estimate the resolution of the human eye. In daytime, the aperture of the pupil is 5 mm = 0.005 meters. Again, we use the wavelength of light is 0.5 microns = 5×10^{-7} meters. From this we get that two objects can be distinguished if

$$B = (L/D)\ R = (5 \times 10^{-7}/.005)\ R = 10^{-4}\ R$$

This is satisfied if

$$B/R = 10^{-4}$$

From trigonometry, this is equivalent to an angle of 0.007 degrees = 0.25 minutes of arc. Excellent vision for humans (20/20 vision) means that the person can resolve things at 1 minute of arc. This is approximately the spacing of rods in the retina of the eye. So we can't quite see at the diffraction limit.

If we had closer rods in our eyes, we could see better. This is probably what gives certain animals, such as eagles, better vision than humans.

holograms

Holograms are considered very mysterious by many people, but in fact they are no more mysterious than are mirrors. When a light wave hits a mirror, it makes the electrons in the metal surface to shake. Under such shaking, they emit waves, and these emitted waves are what give us the image.

Suppose we could get the electrons to shake in just the right way, without having an incident light wave? Then they would still emit the light that gives the virtual image. That is exactly what a hologram does. It "records" the wave that, on a mirror, would give a virtual image. Then, when hit with light, it reproduces the wave that give the image.

A hologram could not work except for the fact that light is a wave. A hologram is, in essence, a frozen mirror. It preserves the kind of wave that is reflected, and then creates it when hit with light.

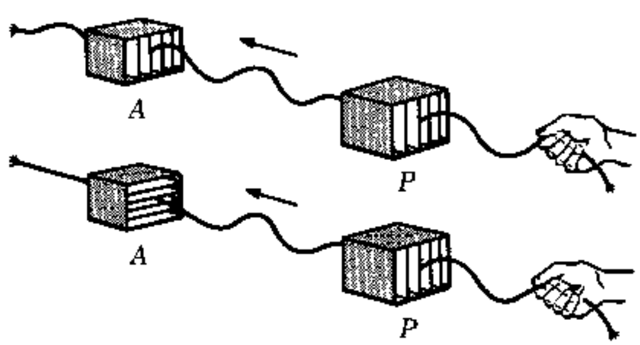
Polarization

Light is a transverse electromagnetic wave. That means that the direction of the electric field is perpendicular to the direction that the wave is moving, just as the shaking of a rope wave is perpendicular to the direction of the rope.

Electromagnetic waves, like rope waves, are polarized. If the electric field is in the vertical direction, we say the wave is vertically polarized. It can also be horizontally polarized. By convention, any other direction of polarization is seen as a combination of vertical and horizontal. For example, a wave polarized at 45 degrees from the horizontal can simply be said to be oscillating in the vertical and horizontal directions at the same time.

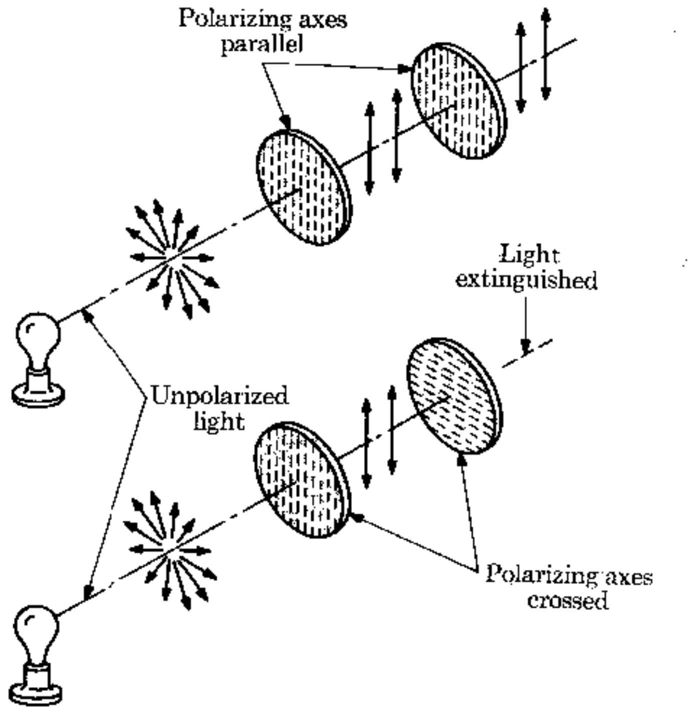
Polarization has become extremely important in modern technology. Liquid crystal displays (used on computer and TV screens) are based on switchable polarizers (we'll discuss this soon). Polarization all gives us a fascinating insight into materials, rocks, and microscopic creatures. We'll discuss these applications in a moment.

Ordinary light (from a light bulb, from the sun) usually consists of many different waves all coming at the same time. As light comes from different atoms in the source, each little part of the wave can have a different polarization. Such light is said to be "unpolarized." The light can be made to have a single polarization by passing it through a material called a polarizer. To understand this it is useful to think about rope waves passing through a picket fence. In the diagrams below, the fence will pass only waves that are polarized in the matching orientation.



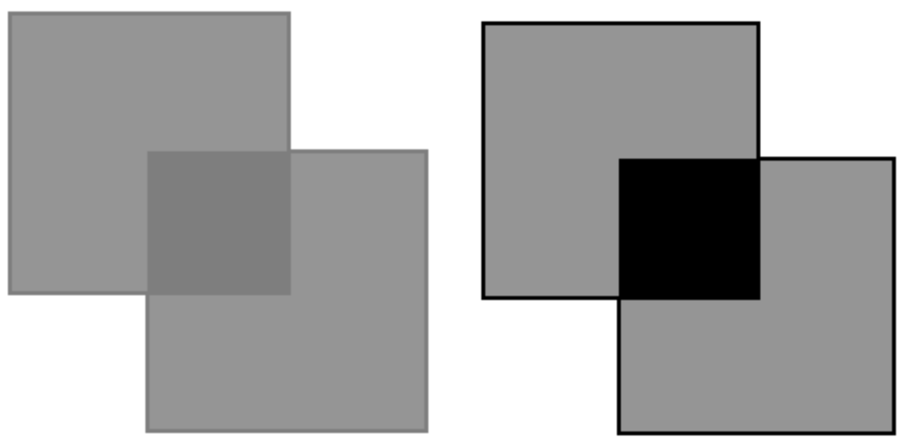
borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm

Thin films that do the same thing were invented by Edwin Land, and trademarked under the name "polaroid". (The Polaroid company later made cameras, but their initial work was solely polaroids.) Polaroid films are also used today in sunglasses. As with the ropes, the film passes only one kind of polarization at a time, as shown in the diagram below.



borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm

Unpolarized light, when it passes through a polaroid, emerges polarized. If it then hits a second polaroid, it will pass through – provided the polaroid is oriented in the same direction. If the second polaroid is oriented perpendicular to the first, then the light is stopped. This is illustrated in the diagram below.



In the left figure, the two polaroids are both vertical. In the right figure, the top one is vertical and the bottom one is horizontal.

borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm

polaroid sunglasses

There are other ways to polarize light. When light bounces off the surface of glass or water or even asphalt (and other non-metals) then the light tends to become polarized in the horizontal direction. If you are fishing, and want to see into the water, and you don't want to be distracted by light reflecting off the surface of the water, then you can take advantage of the fact that the bouncing light is polarized. Wear sunglasses made out of polaroid film, with the film oriented such that it will pass only vertically-polarized light. Then it will stop the reflected light, but half of the light coming from the fish will still be visible.

Polaroid sunglasses advertise that they "cut glare." What they really cut is light that has been reflected off non-metal surfaces. When light bounces off a metal it does not become polarized, so such sunglasses don't help for that kind of glare.

crossed polarizers

When light passes through a transparent material such as plastic, then internal (and normally invisible) stresses in the material can rotate the angle of polarization. Moreover, different colors will be rotated by different amounts. If a horizontal polarizer is placed below the object, and a vertical one is above it, then no light will be transmitted unless there are stresses inside the object that rotate the light. This effect is seen in the image below.

borrowed from Hewitt:
http://www.arborsci.com/Products_Pages/Light&Color/Light&Color7.htm

This effect can be useful in the design of engineering structures. You build a model out of plastic, and view it with crossed polarizers. Then you put a force on the model. The regions of the model that are stressed the most will show up in color. This way you can determine which parts of the structure are most likely to break, and the design can be changed (if necessary) to relieve some of that stress.

liquid crystals

Liquid crystals are materials which act like polaroid film, except that their ability to polarize can be turned on and off with an electric voltage. If you have crossed polarizers, and one is a liquid crystal, then the amount of light coming through can be changed with an electronic signal.

Many thin-screen computer displays take advantage of this. The term "LCD" refers to "liquid crystal display." Laptop computer displays are usually liquid crystal displays with fluorescent lights behind them. If the polarizers are completely crossed, then no light gets through. If they are parallel, then the maximum light comes through. If they are oriented (electronically, remember) at 45 degrees, then half of the light comes through.

3-D movies

When you look at a nearby object, your two eyes are seeing it from a different angle. Your brain notices this, and interprets it to mean the object is close. If the object is far away, the light enters the two eyes from nearly the same direction. Your brain interprets this as meaning that the object is far.

To watch a 3-D movie, you wear special glasses. The most common of these are polaroid glasses, in which the two polaroids are crossed – so they see different light. One could be vertical and the other horizontal.[8] The projected movie actually consists of two separate movies, one for each eye. One movie shows what would be seen by your left eye, and the other shows what would be seen by your right eye. It is the fact that these two images are different that gives the 3-D image.

There are other types of 3-D imaging that don't use polarizers. Some computer screens designed for 3-D blink back and forth between two images. Special blinking goggles then allow you to see with each eye only the image meant for that eye. 3-D postcards are actually double images, with each image divided into strips, and the two images alternating. Over the double image is a series of plastic ridges that bends one image towards your left eye, and the other towards your right eye, so each eye gets a different image.

Summary

Visible light is an electromagnetic wave with wavelength of about 0.5 microns and frequency of about 6 $\times 10^{14}$ Hertz (cycles per second). According to Shannon's

[8] In practice, one is usually oriented at 45 degrees to the right of the vertical, and the other at 45 degrees to the left. That way they are still 90 degrees different from each other.

theorem, this high frequency allows light to carry a high number of bits per second, which is valuable for communications.

Color is the frequency of the light. We detect this by having three sensors in our eyes, sensitive to Red, Green, and Blue. We can fool the eye into thinking that we have a full spectrum of white light with a computer screen by exiting all three of these sensors. Multispectral analyzers do a more complete job, and see colors that we can't distinguish. Printed colors use Magenta, Cyan and Yellow, since they absorb light rather than emit it.

The fact that light is a wave can be seen in the colors of a soap bubble or oil slick. Light reflecting from the front and back surfaces reinforces and cancels (i.e. interferes) and gives rise to the colors.

The simplest device to make an image is a pinhole camera. The image is upside-down. If the pinhole is large, the image is brighter, but blurred. Mirrors make "virtual" images, which appear real, but have no light passing through them. Three mirrors arranged as a corner will reflect light back to the source. That configuration is useful when you want to send light somewhere and have it bounce back towards you. This has been done on the moon with visible light, and is useful for radar (a form of low frequency light).

Stealth is a system used by the military to avoid detection by bounced radar. It is based on two ideas: no corner reflectors, and high absorption (i.e. it is "black").

When traveling through air, water or glass, light travels slower than the speed c in the vacuum. The slowing factor is called the "index of refraction" n. Light bends just the same way that sound bends, towards the slower side. That explains mirages and lenses. A lens, by focusing light, allows a camera to have a "big pinhole" without too much blurring. The blurring of light of wavelength L for an aperture of diameter D at a distance R is given by $B = (L/D) R$. Such blurring means that a spy satellite at geosynchronous orbit would not be able to distinguish objects on the ground that were closer than 7 meter. But from low earth orbit, they could see objects as close as 2 inches.

Different colors have different values of n, and that explains prisms, diamonds, and rainbows. This property is called dispersion, and among jewelers is called "fire." Fire makes diamonds and cubic zirconia crystals colorful and beautiful.

Eyes are like cameras. They have two lenses, the cornea and the flexible "lens". As we get older, the lens loses its flexibility, and we use reading glasses and bifocals to compensate.

Large astronomical telescopes such as Keck need large apertures to collect the light from dim objects. Space telescopes such as Hubble can see smaller objects because they don't have distortions from the Earth's atmosphere.

Holograms work by reproducing the wave that would be present if the object were reflecting its light off a mirror.

Light is transverse, and if all the light in a wave is vibrating in the same direction we say it is polarized. Polarization can be described as horizontal, vertical, or some combination. Polaroid film can be used to turn unpolarized light into polarized. Light reflected from a non-metallic surface becomes polarized, so such glare can be reduced by polaroid sunglasses. Plastic materials placed between crossed polaroids show their internal stresses, and that is useful for analyzing such stress.

Short questions

For the Hubble telescope, which light gives the most blurring?

( ) red
( ) white
( ) blue
( ) infrared

Which signal would give the best number of bits per second in fiber optics?

( ) red
( ) white
( ) blue
( ) infrared

Old people use reading glasses because they

( ) are farsighted
( ) are nearsighted
( ) have very flexible (weak) lenses
( ) have lost the focusing of their cornea

Beads can be used as retroreflectors. This is similar to

( ) laser
( ) red eye
( ) hologram
( ) Keck telescope

Cubic zirconia are most expensive when

( ) they match diamond in dispersion
( ) have the most fire
( ) they are almost as hard as diamond
( ) they have the greatest index of refraction

Rainbows illustrate

( ) diffraction
( ) refraction
( ) dispersion
( ) interference

Mirages occur because

( ) light refracts
( ) light disperses
( ) light interferes
( ) light diffracts

For good resolution, a spy satellite should

( ) be in geosynchronous orbit
( ) use infrared light
( ) be traveling slowly
( ) have a large aperture

When the pinhole is made small, the image becomes

( ) less blurred
( ) smaller

( ) brighter
( ) larger

Essay questions

Newton thought light was a particle, but we now know it consists of waves. What behavior makes light appear to be a particle? How do we know it is a wave?

If you were designing a spy satellite, to take photos of the ground, what considerations would you take? Discuss the height of the satellite and how you would pick it, depending on needed resolution and time over target.

We are all colorblind. Discuss the meaning of that statement. How can instruments do better than human eyes? What is the value of such instruments?

A scientist argues that a fly has better vision than a human, in the sense that the fly can distinguish things that are closer together than can a human. Is that possible? Discuss the relevant physics.

Light doesn't always travel at "the speed of light." Describe the meaning of that paradoxical statement. What are the implications? What phenomena and what inventions depend on this fact?